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Supporting Students: Using Anthropomorphic Structures to Enhance Early Structures Education

Abstract

After two classmates had lifted her off the ground by pulling her arms and legs apart, a smiling but somewhat weary student rolled over on the ground, looked up, and asked, "Are you sure this is architecture?" It was a fair question. An hour later, after her group had been shown the similarities between the structure they'd built with their bodies and the roof of Madison Square Garden, the connection became clearer.

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Supporting Students: Using Anthropomorphic Structures to Enhance Early Structures Education

Rob Whitehead | Iowa State University

Reframing a Structural Sequence:

"The process of visualizing or conceiving a structure is an art. Basically it is motivated by an inner experience, by an intuition."—Eduardo Torroja, 1958

After two classmates had lifted her off the ground by pulling her arms and legs apart, a smiling but somewhat weary student rolled over on the ground, looked up, and asked, "Are you sure this is architecture?" It was a fair question. An hour later, after her group had been shown the similarities between the structure they'd built with their bodies and the roof of Madison Square Garden, the connection became clearer (Figure 1).



Fig. 1 In an attempt to create the largest spanning structures, beginning students intuitively enact the key components of a tensioned cable roof.

Learning to Visualize Behavior:

This paper will argue that structural design courses for beginning architectural students should aspire to directly and immediately teach the important relationship between forces, structural behavior, and the array of potentially responsive architectural forms. Although critically integrating structures in a design requires an elevated technical acumen, students and instructors need not automatically feel apprehension about starting to learn these lessons. A pedagogical approach that focuses on enhancing visualization through hands-on experiences can be matched to address these challenges. These changes should begin with the way information is presented and the expectations for how it could be learned.

When architecture students are taught structures using the deductive teaching methods typically used by engineers, it limits their potential for learning simply by the way the information is presented. The deductive method incrementally reveals isolated lessons by focusing on the selection and assessment of discrete structural elements. This obscures the larger context for the learning and unnecessarily delays the opportunity for students to make conceptual connection between structures and architectural design for years (Felder, 1988). Students want to know what they are sizing, why they would size it, and how this learning fits in with a larger view of structures in architecture.

The opposite approach, induction, is better suited to promote the types of inquiries and discoveries needed in the problem-based design curricula of architecture. Inductive teaching begins by presenting examples of how a concept can be used in practice and asks students to make certain connections (some simple, some complex) as to how the concepts can be applied in practice (Michalski, 1983). But beginning design students have a difficult time imaging and visualizing structural behavior in complex systems so students need to be given specific activities that help them make these inductive connections more effectively.

If one can't "see" what's going to happen in a structural system, it's more difficult to imagine an apt design response. Unfortunately, the mathematical formulae and two-dimensional representations primarily employed in a conventional pedagogy are poor methods for promoting visualization skills of complex three-dimensional structural behavior. Therefore, an effective pedagogy must aspire to impart knowledge about these structural behaviors in a manner that enhances the student's capacity to visualize the potential behavior and understand these types of physical phenomena. The first step is to create an active learning environment that uses haptic learning methodologies, such as the testing of physical models (Williams & Franklin & Wang 2003). Testing scaled physical models is a great learning activity, but test results may be more effectively understood by experienced students (Severud, 1961).

As an effective alternative, students can use a structure they are already familiar with—their bodies—to help them better visualize and understand structural principles. Engaging students in simulations that use their bodies enhances their reasoning about the potential physical behaviors more effectively than the use of visual imagery alone (Barsalou 2008). Ultimately, integrating exercises that explore the relationship between the body and the physical world improves the ability to visualize abstract behaviors and helps to develop embodied cognition (Han, 2011). Students need to know that they already have an intuitive understanding of structural behaviors.

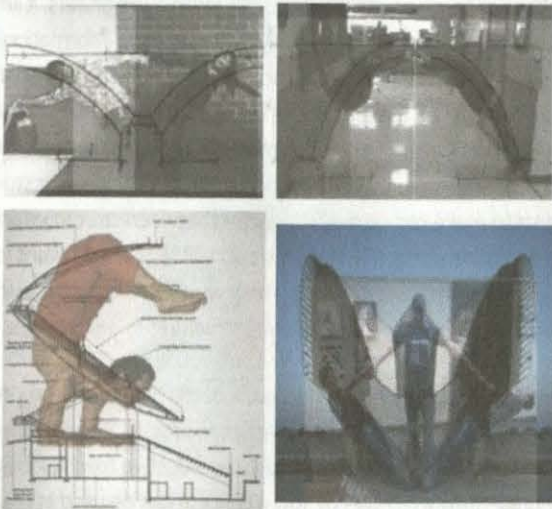


Fig. 2 Examples shown to students of how body positions can help explain structural forms and static behavior.

How the Body Finds Responsive Structural Forms:

"There is nothing more noble and elegant from an intellectual viewpoint than this: to resist through form." —Eladio Dieste, 1992

Initial exposure to complex topics can often make a significant difference in long-term learning efficacy and enthusiasm, so this Anthropomorphic Structures lab is the first structural lab project presented to Iowa State University architecture students. By asking students to construct lightweight structural conditions that mimic real world conditions, students are given a chance to experience, analyze, and describe the resulting structural behaviors. Although there are difficult concepts about structural performance underlying the activities, because they are able use their bodies, students are given a chance to make intuitive connections between what they felt and what they've "built."

In the lecture that occurs one hour before the lab begins, students are reminded that they've all cultivated an incredibly well refined application of structural principles throughout their lives (Zannos, 1987). Any time they balance themselves, lift an object, or walk across campus in the wind carrying their portfolio, their bodies make instantaneous adjustments to maintain equilibrium. They are shown examples of certain anthropomorphically inspired structures are asked to make inductive connections between the examples shown and their assigned exercises (e.g., "how can your intuitive experiences help you intentionally design a structure that works?") (Figure 2).

Students are taught that it's an imperfect testing system because unlike structures, our bodies are designed to be dynamic. We have numerous moveable joints with many degrees of potential rotation that make static positions difficult to maintain. They are reminded that under certain conditions, when their arms hurt, or their backs get sore, they may simply be experiencing an elevated level of stress that results from their body's structural form, and these conditions can be made a part of the potential lesson (Figure 3).



Fig. 3 In an attempt to create a cantilever “shelf” the student group discovers that the hips/waist area are a weak point.

The Fun Times & Serious Business of Building Body Structures

As a means of simplifying the relatively complicated possible structural conditions, the lab intentionally presents two simple and easily understandable categories of structural challenges: *How far can you span?* and *How high can you reach?* The process of standing, reaching, and holding objects is so common that students often fail to recognize these seemingly innocuous activities solve the same structural challenges of “stacking and spanning” that all structural designers face. There are subsets and modifications of each pose that are designed to provoke the more specific lessons. To help students conceptualize, visualize, and communicate the structural behavior between team members, students were asked to take photographs during the lab and to keep a record of their lab activities and observations (“Show me where you feel it”).

Although students are encouraged to have fun, there are serious learning objectives tied to their activities that require a demonstrated level of understanding. The most important lesson is the relationship between the location and magnitude of forces within a structurally responsive form—specifically how modifications in the form can be made to more effectively resist the forces in a stable configuration (Dermody, 2010). But to have the inductive teaching method work effectively, students also need to make connections back to the foundational structural topics that make these configurations possible including:

- Forces & Loads: The sense, direction, and magnitude of forces caused by concentrated or distributed dead loads and live loads.

- Stress & Strain: The ability to identify and understand the different effects of compressive, tensile, bending, shear, and torsional stresses on a physical body.

- States of Equilibrium: Why static structures don’t fall down (translational equilibrium) or tip over (rotational equilibrium).

After allowing students to experience the structural behaviors with their bodies, and discussing particular observations with them during their exercises, students were asked to develop representations of what they “built” and experienced (using pictures, diagrams, and descriptions) in a lab report.

Teaching Stability & Equilibrium:

In conventional structures courses, many of the first deductive lessons about structural behavior focus on forces and equilibrium. Forces are shown as two-dimensional arrows and equilibrium is presented as a product of equalizing mathematical and geometric conditions. In this lab, they are able to visualize and “feel” equilibrium because they are using their bodies to simulate different loading conditions (especially with differently sized team members). They find translational and rotational equilibrium in the simplest way—by not falling down or tipping over. And although they’ve see the two-dimensional vector arrows that are meant to describe equilibrium, they frequently comment upon how unhelpful this representation is to describe the three-dimensional complexity they feel.

In one particularly helpful spanning exercise, two students hang off of each side of their middle teammate (Figure 4). All three people put their feet together in the side students slowly reach outward to create a relatively long spanning double cantilever diamond-shaped structure. This pose teaches several key lessons about stability: the weight of the hanging students should be relatively balanced or it doesn’t work (rotational equilibrium side to side), all the feet need to be grouped tightly together at one point (concurrent forces and rotational equilibrium front and back), and it demonstrates the natural formal rigidity of a triangle in a system (between their arms, torso, and feet). Few students can hold this pose for a long time because of the internal stress felt in their arms. Students are required to discuss the type of stresses they felt and diagram their locations in the lab report.



Fig. 4 The double cantilever spanning pose teaches critical lessons about rotational equilibrium, the difference between compression and tension, and the value of strong connectors (at the hands).

Other students choose to forgo this long span option for the more radical solution where one student is held in suspension between two others, like the roof of Eero Saarinen's Dulles Terminal. The spanning student's body naturally hangs down in a funicular shape and is subjected to tension throughout the body. This basic configuration provides an opportunity to talk about axial stresses and direction of forces in a system—the two supporting students often lean back with their entire body, pulling as a means of creating resisting thrust (Figure 5).

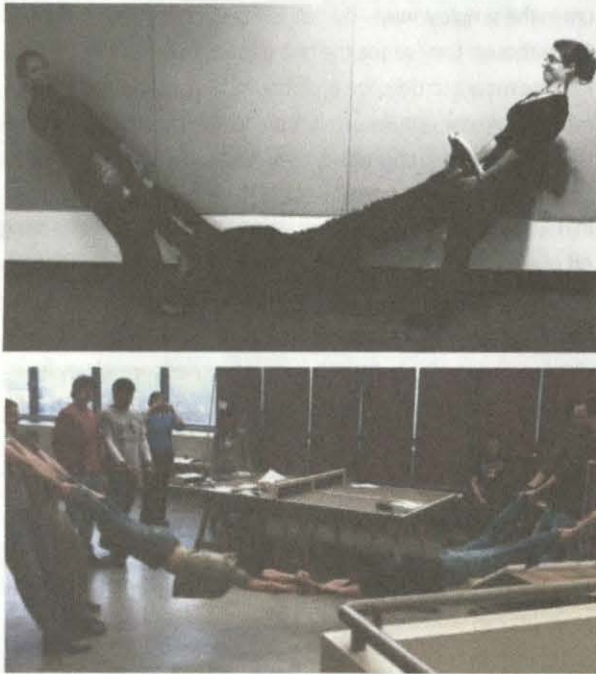


Fig. 5 The form-resistant hanging chain pose is a popular experiment. Several groups have tried to make a longer span but the amount of outward thrust and high levels of tension stress felt in their hands limits their options. These “failures” are the way of understanding how the structure really works.

With poses like this, students first learn about “form-resistant” structures (such as cable and arches). Initially, without prompting, the middle student's body always hangs like a cable, but when they are challenged to stiffen their body into a flatten beam-like structure, they realize how much more difficult it is to try and maintain a static form when their body is subjected to bending stress. They feel the stress in their back and abs and instantly understand the internal force couple of compression and tension in opposite end fibers of a beam—even if they can't apply this knowledge to bending theory, they now know what it feels like and how to simulate this learning for later. They often find other exercises that also cause them to feel bending stress—they don't hold the poses for long (Figure 6).

Other types of stresses, such as moment forces, bending, and torsion are also easily demonstrated in the spanning/reaching exercise. The concept of moment force is perhaps most easily taught by simply asking students to hold a weight away from their body at various lengths—obviously the further away the weight is held, the more their shoulder has to generate an internal resisting “moment” to keep their arm from falling down. Simple mathematics are introduced here alongside other physical examples of shelf brackets and tree branches to show how certain shapes are designed to be form resistant against these particular types of stresses (Figure 9).



Fig. 6 Experiments with forms that create bending stresses. Tension and compression are typically felt in the abs and back immediately.

Stress & Strain in Stacked Configurations:

For the stacking exercise, students often build a pyramid-like structure with their bodies with two people on the bottom supporting a third in the middle. Intuitively they come to realize that the weight of their bodies (or props) are the loads in the system and these loads created different types of stresses (compression, tension, bending or shear) depending on the configuration. Because students are stacked on top of each other, this exercise allows them to feel the impact that additive loads have on the base of a structure (Figure 7). When students are able to feel how much harder this is with one person on top of another, it is much easier to imagine the increased magnitude of forces and weight that act upon multi-story buildings. They learn that when these body parts begin to ache, or move, that this is the strain caused by the structural stresses.

Some body parts are better equipped to handle different stresses than others, so students intuitively adjust their poses accordingly. The two supporting students often use their knees,

waist or shoulders to support the weight of the third teammate so the load transfer is more directly transferred downward. Interestingly, students at the base of the structure nearly always triangulate their feet by shifting them forward and backward and side-to-side. Typically this weight shifting is an uncoordinated effort between teammates that is often unspoken and intuitive—although this is always pointed out after they've completed the stance because it is such an important point.

These structures typically fail eventually not because the stance of the supporting students is out of equilibrium, but because the compressive stresses accumulate and fatigue the legs of the students nearly to the point of causing buckling. In later semesters when discussing the need to provide buckling resistance for compressive elements, such as columns, this lesson is brought up as an example.



Fig. 7 Stacked Configurations. The location and configuration of the support points from the top student(s) to the supporting students is a critical item to focus on because it reveals many critical structural issues about force transfer, geometry, and pinned connections.

These body structures look relatively stable once the students are in their final pose, but because the “construction staging” of these structures is often quite complicated, they are asked to describe how the states of equilibrium change during this process. Ideally this will help them see how structures aren't just a final static form but are a result of a dynamic process of construction.

Reflective Learning in Lab Reports:

To help achieve the learning objectives, student lab reports are required to address several questions put forth in the handout. The labs are modeled after other scientific lab reports so they are asked to include descriptions of their hypothesis (including early sketches), implementation process, testing (weights and measurements), test results (mode of failure), and a conclusion

of critical lessons learned. The types of representations required in these early labs are intentionally left somewhat open-ended to give students the leeway to experiment with different ways of best representing what they learned. Most students reflect the inductive pedagogical process in their description. For example, they often show their final pose first and use photos, sketches, and other images and descriptions to describe how the concepts are integrated into their proposal (Figure 8).



Fig. 7 In their lab report, this student group explained how their body structure worked by comparing it to a constructed prototype and the Eiffel Tower.

Although most student groups thrive in creating and explaining their body structures, their initial graphic representations and written descriptions are severely under-developed. This is to be expected as they haven't been taught these specific skills yet, but it is interesting to see the disconnection between what they experience (e.g., equilibrium as a three-dimensional problem) and the conventional over-simplified version of these events that they represent (e.g., large arrows pointing up and down overlaid on a photo of their pose).

Because it is important to translate structural behaviors into graphic representations, we spend the entire next lab reviewing their labs and teaching them ways to graphically represent forces, loads, and states of equilibrium. In a way, we have to reverse engineer their perceptual experiences to help them to visualize how to graphically represent the abstract behaviors they've experienced.

They also have to be taught how to write about their lab experiences with a critical and inquisitive voice. Most of the first drafts of their labs demonstrated an enthusiasm about the lab activities (e.g., “we had a great time with this pose”) but a conspicuous lack of rigor in the descriptions and comparisons. We show them lab reports from advanced students and assign them readings about the scientific method in lab writings. Students are given a chance to redo the lab and resubmit it for final evaluation and nearly universally the results of the labs improve dramatically (Figure 9).



Fig. 9 Images from first lab reports show the challenge of representing their experiences graphically.

Results, Revisions, and Assessments:

Although there is a clear advantage to haptic learning methods that tap into intuitive understanding of structural performance, learning structures only by using one's body has very specific limitations. Our bodies can only create a handful of loading arrangements, can only endure a limited amount of stress, and the possible range of our body forms and gestures can only be used to communicate a small range of structural behaviors. Therefore, as a subsequent follow-up to this lab, students were asked to "translate" their personal experiences of structural behavior into a three-dimensional model built with spaghetti and hot glue. These structures were tested with weights and students were asked to comment on the similarities and differences of the structures and their performance that resulted from the change in material and connections.

By encouraging students to safely push the physical limits of their bodies during these exercises, they were able to learn critical and insightful lessons about the limitations and internal stresses present in many structures, including the fundamental idea that there is an important relationship in efficient and ef-

fective structures between the applied forces and the resisting forms.

Because I teach the entire structural design sequence, I can attest to the ways in which this assignment has had a positive lasting impact on the remainder of their structural education. In many lab reports completed in later semesters, students often make references in their descriptions of behavior and modes of representations, to the "body structures." Typically these observations are found in form-active structural analysis labs (cables and arches), in the description of "buckling" in column and beam behavior, and in relation to structural connections (e.g., equating pin connections performing like ankles in a body).

At the conclusion of their structural sequence, students are asked to select a long span structure to analyze in great detail—perhaps not coincidentally, two popular choices are Madison Square Garden and Dulles Airport Terminal. Gratifyingly, these projects are usually quite well understood.

Notes

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